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EFFECTIVENESS OF FIVE WATER-COOLED UNDERGARMENTS IN REDUCING HEAT STRESS OF VEHICLE CREWMAN OPERATING IN A HOT-WET OR HOT-DRY ENVIRONMENT

US ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
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The auxiliary cooling provided by five water-cooled undergarments was directly measured on a life-size, sectional manikin. Each water-cooled undergarment was worn with a combat vehicle crewman (CVC) ensemble, with or without a complete chemical protective (CB) suit. Cooling rates (watts) were determined for both dry (non-sweating) and completely wet (maximal sweating) skin conditions. The watts of heat removed from either the dry or the completely wet skin surface were found to be almost directly proportional to the temperature difference between the manikin skin temperature and the cooling water inlet

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) temperature; the cooling represents the absorption of heat directly from the body, plus any heat that is received by the body from a hot environment. The cooling density, expressed in watts of cooling per square meter of cooling tube array, differed with the size of the array and with the location of the skin surface it covered. Comparison between the dry skin and the completely wet skin surface and the completely wet skin cooling rates showed a synergistic effect over those areas covered by a water-cooled undergarment; i.e. the total watts of cooling over a completely wet skin area (head, torso, etc.), minus the expected evaporative heat loss from the same skin area to the environment, were considerably greater than the watts of cooling when the skin was dry.

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(6) Effectiveness of Five Water-Cooled Undergarments in Reducing Heat Stress of Vehicle Crewmen Operating in a Hot Wet or Hot Dry Environment

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FOREWORD

A systematic program for the assessment and development of a variety of auxiliary cooling undergarments and supporting equipment is in progress. This sectional manikin study directly measured the cooling (in watts) provided by each of five water-cooled undergarments; this is one phase of a series of efforts that will be undertaken to provide a technical basis for selecting an auxiliary cooling system for combat vehicle crewmen. Following this study, those auxiliary cooling systems which appear to show the most promise will be examined in a physiological study using human volunteers in tests exposed to hot environments in the Tropic Chamber.

The Project Officer for the US Army Natick Laboratories, Joseph Fratantuono, was responsible for the technical work unit under which this study was carried out; he supplied the water-cooled undergarments and cooling equipment for this study.

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ABSTRACT

The auxiliary cooling provided by five water-cooled undergarments was directly measured on a life-size, sectional manikin. Each water-cooled undergarment was worn with a combat vehicle crewman (CVC) ensemble, with or without a complete chemical protective (CB) suit. Cooling rates (watts) were determined for both dry (non-sweating) and completely wet (maximal sweating) skin conditions. The watts of heat removed from either the dry or the completely wet skin surface were found to be almost directly proportional to the temperature difference between the manikin skin temperature and the cooling water inlet temperature; the cooling represents the absorption of heat directly from the body, i.e. produced by the metabolic processes of the body, plus any heat that is received by the body from a hot environment. The cooling density, expressed in watts of cooling per square meter of cooling tube array, differed with the size of the array and with the location of the skin surface it covered. Comparison between the dry skin and the completely wet skin cooling rates showed a synergistic effect over those areas covered by a water-cooled undergarment; i.e. the total watts of cooling over a completely wet skin area (head, torso, etc.), minus the expected evaporative heat loss from the same skin area to the environment, were considerably greater than the watts of cooling when the skin was dry.

EFFECTIVENESS OF FIVE WATER-COOLED UNDERGARMENTS IN REDUCING HEAT STRESS OF VEHICLE CREWMEN OPERATING IN A HOT WET OR HOT DRY ENVIRONMENT

I. INTRODUCTION

Personnel operating in unventilated armored fighting vehicles in hot environments can be exposed to temperature and humidity combinations which reach thermally intolerable levels (5,6). Under these extreme environmental conditions, the operational performance of these combat personnel can be seriously impaired, even when they are operating at low activity levels. When the hatches of these vehicles are closed during periods of heavy engagement, or during a chemical, bacteriological (CB) attack, the heat stress imposed on these combat crewmen could minimize their effectiveness in battle either by reducing their operational efficiency or by causing them to become heat casualties. It is becoming more evident that some form of auxiliary cooling for these combat vehicle crewmen is a basic requirement for their survival in hot environments (4).

A study completed about three years ago (2) investigated the cooling provided by four different water-cooled undergarments. This cooling, directly measured on a sectional, heated copper manikin, represents the absorption of the heat produced by the metabolic processes of the body, plus the heat from the ambient environment in the vehicle. A dry (non-sweating) skin was used as the heated surface of the body, from which heat was transferred to the cooling water flowing in the tubing of a water-cooled undergarment. This experimental procedure assumes that the heat removed from the skin surface by a water-cooled undergarment is sufficient to maintain the skin surface temperature below the 35°C level at which sweating would occur. However, under conditions of more severe heat stress (e.g. 51.7°C, 25% relative humidity) the skin temperature rises and sweating occurs; this would not only wet the skin but would also wet the water-cooled undergarment and clothing layers as well. Schutte, et. al. (8) in their recent heat acclimatization study postulated that those areas underneath a cooling garment would show a decrease in sweating because of the cooling effect on the skin but that other body surface areas would still produce sweat and might over-respond.

The present study investigates the heat exchanges, in two hot environments, from a dry (non-sweating) skin, and also from a completely wet (maximal sweating) skin surface, to the cooling water flowing through the tubing of a water-cooled undergarment. When a water-cooled undergarment covered more than one manikin section, both the total cooling and the amount of cooling over each individual section was directly measured and expressed in electrical watts. Each of the five water-cooled undergarments was worn with the combat vehicle crewman (CVC) ensemble with the complete chemical protective (CB) suit; two of these water-cooled undergarments were also worn with only the combat vehicle crewman ensemble. To accommodate the range of activitiy levels of CVC crewmen, which could vary from a minimum activity of about 80w to a high activity of about 400w, these water-cooled undergarments ranged from a simple water-cooled cap, which covered the head, to the "water-cooled undergarment, long", which covered the head, torso, arms and legs.

2. EXPERIMENTAL METHOD

The electrically heated copper manikin consists of six sections: head, torso, arms, hands, legs and feet. This manikin was placed in a standing position in a large temperature and humidity controlled chamber (chamber test dimensions are: length 5.8m, width 3.9m, and height 2.7m); chamber environmental conditions were either 29.4°C (85°F) at 85% relative humidity or 51.7°C (125°F) at 25% relative humidity.

The cooling water supplied to a water-cooled undergarment passed through a heat exchanger which was temperature controlled, and was monitored by a thermocouple placed in the inlet tubing at the entrance to a water-cooled undergarment. A flow meter was used to set the water flow rate at the required value. Temperatures over the manikin surface, air temperature and water inlet temperature to a water-cooled undergarment, plus the power in watts supplied to each of the six manikin sections were continuously recorded during a run. Two steady-state runs were made during each day's experiment for each combination of clothing ensemble, water-cooled undergarment, cooling water inlet temperature and chamber environment.

The heat loss from the manikin surface is determined from the electrical watts required to maintain the manikin surface temperature constant. All cooling rates in this study are based on an average surface temperature of 35°C. Experimentally, these "cooling watt" rates are equal to the difference between the electrical watts supplied to a manikin section(s) when water is flowing through the tubing of a water-cooled undergarment, and the electrical watts supplied when water is not flowing through the tubing; e.g. the heat removed from the torso by the water flowing through the tubing of the water-cooled vest is equal to the difference between the electrical watts demanded to maintain torso temperature with and without water flow. The "total watts" removed from all six manikin sections (head, torso, arms, hands, legs and feet) when water is flowing through the tubing of a water-cooled undergarment was also determined. These total heat exchange rates include the cooling provided by a water-cooled undergarment and hence depend on the heat transfer from the manikin surface, plus the heat transferred to the water directly from the hot environment. These "total" rates are therefore dependent not only upon the clothing ensemble worn but also the hot environment in which the exposure occurs.

The five water-cooled undergarments in Figure 1 include a water-cooled cap which provides cooling to the head; a water-cooled vest which provides cooling to the torso; a water-cooled cap with a water-cooled vest which provides cooling to the head and torso; a water-cooled undergarment, short, which provides cooling to the torso, arms and legs; and a water-cooled undergarment, long, which provides cooling to the head, torso, arms and legs. None of these water-cooled undergarments provide cooling to the hands or feet. Previous results (2) had shown that although cooling increased with increasing cooling water flow rate, the increase in cooling was not directly proportional to flow rate. Therefore, only one cooling water flow rate was used for each water-cooled undergarment; the cooling water flow rate was 22.7 kg/h for the water-cooled cap, vest and cap with vest and was 63.6 kg/h for both the water-cooled undergarments, short and long. Cooling water inlet temperatures were varied over the range 7 to 28°C. The components for the combat vehicle crewman (CVC) ensemble and the chemical protective (CB) suit which were worn over these water-cooled undergarments are given in Table I; photographs of these two ensembles, dressed on the manikin, are shown in Figure 2.

TABLE I

ENSEMBLE COMPONENTS

ENSEMBLE	COMPONENTS
Combat Vehicle Crewman (CVC)	Coveralls, Combat Vehicle Crewman (CVC) Helmet Socks, Men's 40% cotton, 60% wool Black leather boots
	above plus
Closed System (Manikin completely covered)	Suit Chemical Protective Gas mask/hood Rubber gloves

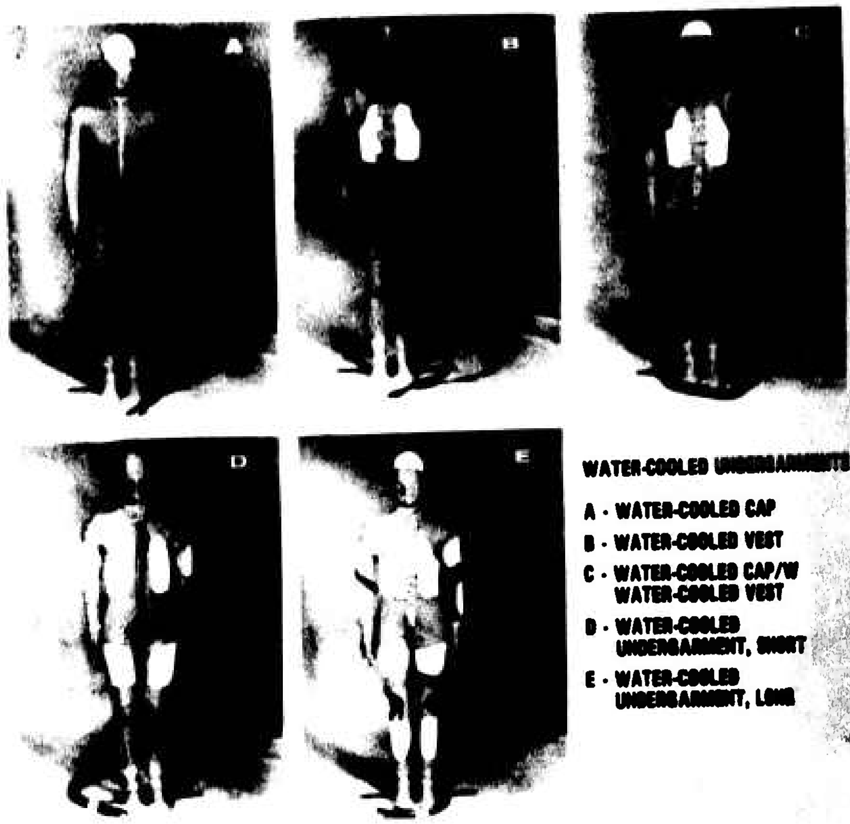

Figure 1. Photographs of the five water-cooled undergarments: A. water-cooled cap, B. water-cooled vest, C. water-cooled cap w/water-cooled vest, D. water-cooled undergarment, short and E. water-cooled undergarment, long.

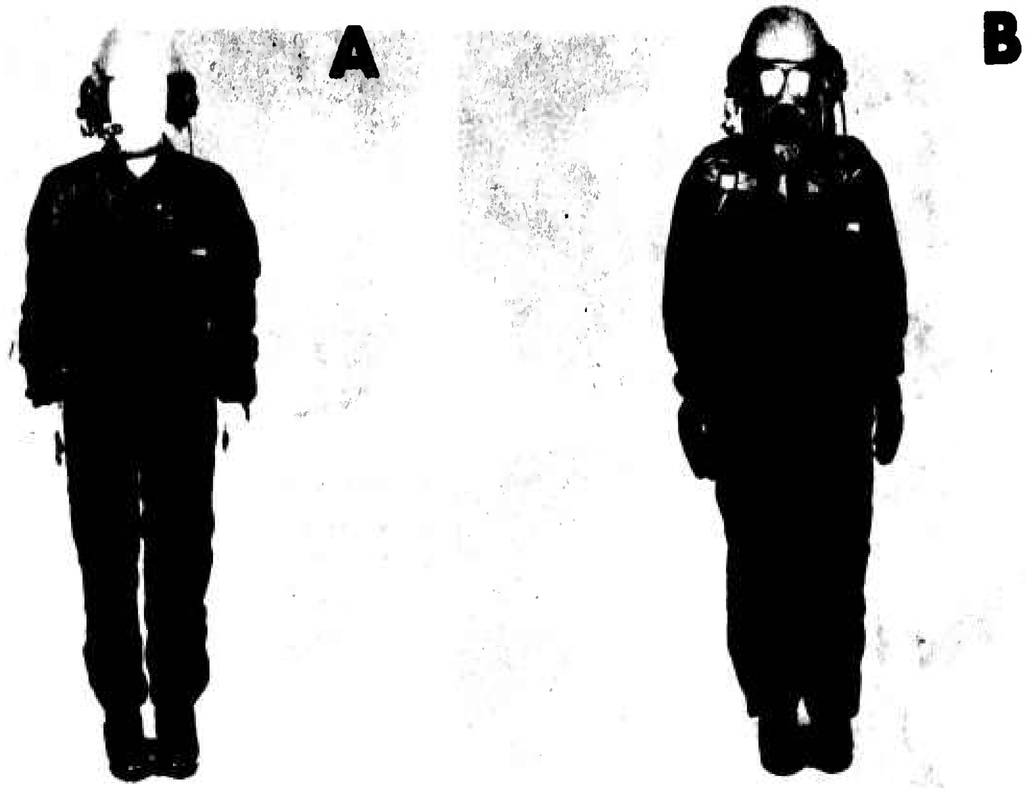

Figure 2. Photographs of A. a combat vehicle crewman (CVC) ensemble and B. a closed chemical protective (CB) suit.

3. RESULTS

A. HEAT TRANSFER PROPERTIES OF THE COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE WORN WITHOUT AND WITH THE CLOSED CHEMICAL PROTECTIVE (CB) SUIT

Table II gives the best transfer properties of the combat vehicle crewman (CVC) ensemble and also of the combat vehicle crewman ensemble with the closed chemical protective (CB) suit. Values of insulation (clo) and evaporative heat transfer (i_m/clo) presented in this table are used to calculate the conductive/convective and the maximum evaporative heat transfer from each of the six sections of the manikin as well as the total heat transfer from the manikin. Figures 3 and 4 graphically illustrate the distribution of the heat transfer to or from the manikin surfaces (skin temperature of 35°C) for these two ensembles during exposure to two chamber environments; a hot-wet or jungle environment of 29.4°C (85°F), 85% relative humidity and a hot-dry or desert environment of 51.7°C (125°F), 25% relative humidity. Both ensembles would permit some dissipation of heat during exposure to the chamber environment of 29.4°C, 85% relative humidity, about 149w for the CVC ensemble and about half as much (70w) for the CVC with the closed CB ensemble. However, with the chamber air temperature increased to 51.7°C (25% relative humidity), both ensembles would restrict evaporative heat loss to a greater extent than their restriction of conductive/convective heat gain. In this latter environment, all metabolic heat input to the body would have to be stored in the body and therefore body temperature would continually increase as long as the body was exposed to this hot environment. The conductive/convective heat gain from this hot-dry environment (51.7°C, 25% relative humidity) is about 20% greater, and the evaporative heat loss is about 30% less, than for a hot, dry environment of 48.9°C (120°F) and 20% relative humidity. These figures (i.e. Figures 3 and 4) illustrate the necessity of providing some form of auxiliary cooling to a combat vehicle crewman dressed in a closed chemical protective suit for an extended period of time in a severe, hot, humid environment. The tolerance time for sustained work by men wearing this type clothing in such a hot, humid environment is only about 30 minutes (3).

TABLE II

HEAT TRANSFER PROPERTIES (INSULATION IN CLO UNITS; THE MOISTURE PERMEABILITY (i_m); AND THE EVAPORATIVE HEAT TRANSFER (i_m/clo)) OF COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE AND COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE w/ CLOSED CHEMICAL PROTECTIVE (CB) SUIT

Manikin Sections	CVC ENSEMBLE ALONE			CVC CLOSED CB SUIT		
	clo	i_m	i_m/clo	clo	i_m	i_m/clo
Head	1.42	.47	.33	2.43	.10	.04
Torso	1.66	.33	.20	3.38	.34	.10
Arms	1.49	.40	.27	2.68	.40	.15
Hands	0.99	.42	.42	1.29	.05	.04
Legs	1.68	.47	.28	3.11	.50	.16
Feet	1.42	.24	.17	1.65	.18	.11
Torso-Arms	1.59	.35	.22	3.10	.37	.12
Torso-Arms-Legs	1.63	.41	.25	3.10	.43	.14
Overall	1.53	.40	.26	2.63	.32	.12

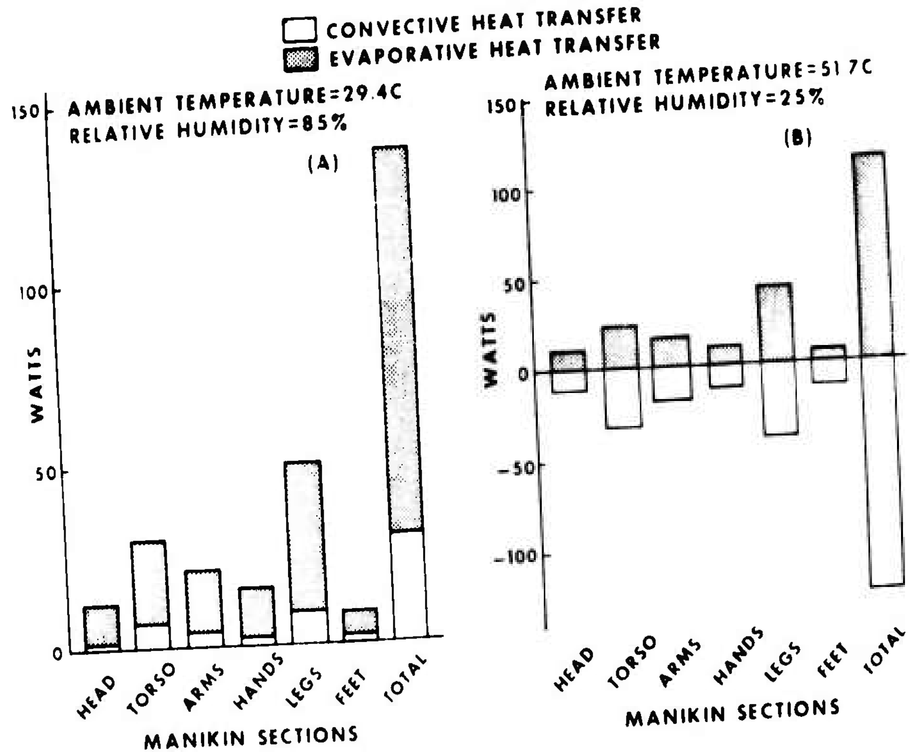

Figure 3. Graphic presentation of the convective and evaporative heat transfer properties of a combat vehicle crewman (CVC) ensemble when exposed to hot environments of A. 29.4°C, 85% relative humidity and B. 51.7°C, 25% relative humidity.

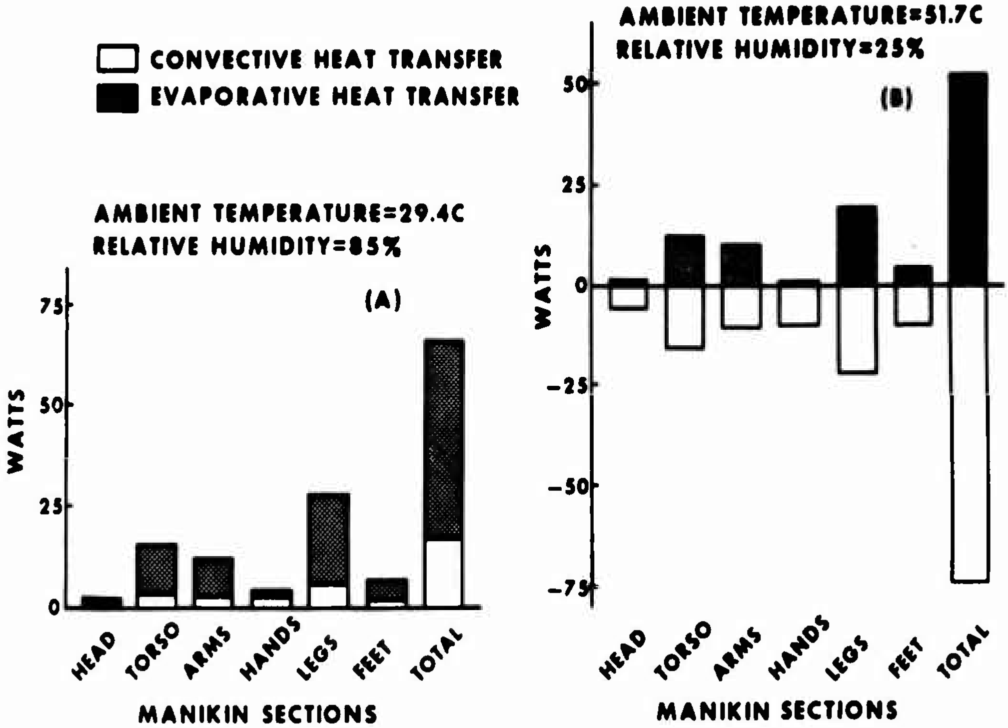

Figure 4. Graphic presentation of the convective and evaporative heat transfer properties of a combat vehicle crewman (CVC) ensemble with closed chemical protective (CB) suit when exposed to hot environments of A. 29.4°C, 85% relative humidity and B. 51.7°C, 25% relative humidity.

B. HEAT TRANSFER PROPERTIES OF THE TWO CLOTHING ENSEMBLES WORN WITH EACH OF THE FIVE WATER-COOLED UNDERGARMENTS

Tables III and IV present the heat transfer properties of these two ensembles worn with each of the five water-cooled undergarments, when there was no cooling water flowing through the tubing. These tables show that the areas covered by a given water-cooled undergarment have an increase in insulation (clo) and a decrease in evaporative heat transfer properties (i_m/clo). The total values of insulation with either ensemble increase as the body area coverage of the water-cooled item increases. For example, a water-cooled cap, which covers only about 4% of the total body surface area, shows little measurable effect on the total, overall insulation; however, the water-cooled undergarment, long, which covers about 39% of the total body surface area, increases the overall insulation provided by the combat vehicle crewman ensemble by about 14% and decreases its potential evaporative heat transfer by about 15%. The percentages of the individual manikin sections and of the total surface area covered by each of these five water-cooled tubing arrays is given in Table V; all these tubing arrays cover less than 50% of a given manikin section, for example, the tubing array of the water-cooled cap covers about 47% of the manikin head surface area.

TABLE III

HEAT TRANSFER PROPERTIES OF COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE WITH ONE OF FIVE WATER-COOLED UNDERGARMENTS WITH WATER IN THE TUBING BUT NO WATER FLOW

CVC Ensemble plus Water-Cooled:

Manikin Sections	Cap			Vest			Cap & Vest		
	clo	i_m	i_m/clo	clo	i_m	i_m/clo	clo	i_m	i_m/clo
Head	1.60	.42	.26	1.42	.47	.33	1.60	.42	.26
Torso	1.66	.33	.20	2.13	.34	.16	2.13	.34	.16
Arms	1.49	.40	.27	1.49	.40	.27	1.49	.40	.27
Hands	0.99	.42	.42	0.99	.42	.42	0.99	.42	.42
Legs	1.68	.47	.28	1.68	.47	.28	1.68	.47	.28
Feet	1.42	.24	.17	1.42	.24	.17	1.42	.24	.17
Torso-Arms	1.59	.35	.22	1.86	.37	.20	1.86	.37	.20
Torso-Arms-Legs	1.63	.41	.25	1.77	.41	.23	1.77	.41	.23
Overall	1.54	.39	.25	1.65	.40	.24	1.65	.39	.24

Manikin Sections	Garment, Short			Garment, Long		
	clo	i_m	i_m/clo	clo	i_m	i_m/clo
Head	1.42	.47	.33	1.60	.42	.26
Torso	2.13	.34	.16	2.13	.34	.16
Arms	1.81	.42	.23	1.88	.36	.19
Hands	0.99	.42	.42	0.99	.42	.42
Legs	1.75	.47	.27	1.83	.44	.24
Feet	1.42	.24	.17	1.42	.24	.17
Torso-Arms	2.01	.36	.18	2.04	.35	.17
Torso-Arms-Legs	1.89	.42	.22	1.94	.39	.20
Overall	1.70	.41	.24	1.75	.38	.22

TABLE IV

HEAT TRANSFER PROPERTIES OF COMBAT VEHICLE CREWMAN (CVC) ENSEMBLE w/ CLOSED CHEMICAL PROTECTIVE (CB) SUIT WITH ONE OF FIVE WATER-COOLED UNDERGARMENTS WITH WATER IN THE TUBING BUT NO WATER FLOW

CVC Ensemble w/ Closed CB Suit plus Water-Cooled:

	Cap			Vest			Cap & Vest		
Manikin Sections	clo	i_m	i_m/clo	clo	i_m	i_m/clo	clo	i_m	i_m/clo
Head	2.57	.10	.04	2.54	.10	.04	2.57	.10	.04
Torso	3.38	.34	.10	3.96	.28	.07	3.96	.28	.07
Arms	2.68	.40	.15	2.68	.40	.15	2.68	.40	.15
Hands	1.29	.05	.04	1.29	.05	.04	1.29	.05	.04
Legs	3.11	.50	.16	3.11	.50	.16	3.11	.50	.16
Feet	1.65	.18	.11	1.65	.18	.11	1.65	.18	.11
Torso-Arms	3.10	.37	.12	3.39	.34	.10	3.39	.34	.10
Torso-Arms-Legs	3.10	.43	.14	3.26	.42	.13	3.26	.42	.13
Overall	2.63	.32	.12	2.71	.30	.11	2.71	.30	.11

	Garment, Short			Garment, Long		
Manikin Sections	clo	i_m	i_m/clo	clo	i_m	i_m/clo
Head	2.54	.10	.04	2.57	.10	.04
Torso	3.96	.28	.07	3.96	.28	.07
Arms	2.83	.37	.13	2.98	.39	.13
Hands	1.29	.05	.04	1.29	.05	.04
Legs	3.11	.34	.11	3.10	.40	.13
Feet	1.65	.18	.11	1.65	.18	.11
Torso-Arms	3.48	.31	.09	3.57	.32	.09
Torso-Arms-Legs	3.26	.36	.11	3.35	.37	.11
Overall	2.74	.27	.10	2.76	.28	.10

TABLE V

PERCENTAGE SURFACE AREA COVERED BY EACH OF THE FIVE WATER-COOLED UNDERGARMENT TUBING ARRAYS

	Cap	Vest	Cap & Vest	Garment Short	Garment Long
Manikin Sections					
Head	47	—	47	—	47
Torso	—	44	44	44	44
Arms	—	—	—	25	47
Legs	—	—	—	30	46
Hands	—	—	—	—	—
Feet	—	—	—	—	—
Torso-Arms	—	26	26	37	45
Torso-Arms-Legs	—	16	16	34	45
Overall	4	12	16	26	39

C. HEAD COOLING PROVIDED BY THE WATER-COOLED CAP

Figure 5A, shows the watts of cooling provided to the head by the water-cooled cap (WCC) as a function of the cooling water inlet temperature. These cooling rates are the heat actually removed from the head by the water-cooled cap; i.e. they are the net difference between the electrical watts measured with water flowing through the tubing of the water-cooled cap and the electrical watts measured without water flow. These data were obtained with the manikin dressed in a combat vehicle crewman (CVC) ensemble with the closed chemical protective (CB) suit and exposed to a 29.4°C, 85% relative humidity environment. The dashed line shows the heat removed from the head (watts of cooling) by the cooling water when the skin is dry (non-sweating); the solid line gives the watts of cooling for a completely wet (maximal sweating) skin condition. The greater cooling effect at a given inlet water temperature when the skin is wet, apparently results from an increased thermal conduction between the skin and the cooling system; the moisture on the skin wets the tubing by condensation of water vapor, thus setting up a continuous cycle of evaporation of moisture from the skin and inner cap followed by condensation of this moisture on the tubing and inner surfaces of the water-cooled cap. This phenomenon was first observed by Breckenridge (1) in his study of the evaporative heat transfer cycle within an impermeable cold weather boot.

This effect of a wet skin was observed for all five water-cooled undergarments; the cooling provided over a dry skin is considerably less than the cooling provided over a completely wet (maximal sweating) skin, even after subtracting the evaporative heat loss to the hot environment that is expected based on i_m/clo values for the ensemble plus water-cooled undergarment (Tables III and IV). Intermediate values of cooling, between these lower (dry skin) and upper (completely wet skin) limits, will occur when the skin is initially dry but then there is either an increase in skin wetted area with the onset of sweating or as the tubing acquires a film of water as a result of moisture condensing out of the air surrounding the tubing and being wicked or compressed onto the skin, water-cooled undergarment material and clothing. This condensation of moisture out of the air surrounding the tubing, apparently is responsible for an increase in the heat transfer from the skin area affected, i.e. moisture condensing on the comparatively small areas of the tubing wicks or blots to the larger, inner surface layers of clothing where it can be evaporated either to the environment or condensed on the inside of the outer clothing layers. Note that for this water-cooled cap to provide 50w of cooling to a fully sweating head would require a cooling water inlet temperature of about 18°C; inlet water temperature would have to be about 0°C for a dry, non-sweating head to obtain the same cooling. However a 0°C inlet temperature would produce noticeable pain to sensitive areas of the head, i.e. over the eyes. Cooling water inlet temperature less than 5°C would be required to provide 100w of cooling to a sweating head. This also would produce noticeable pain over sensitive areas of the head; for a dry skin condition, 100w of cooling could not be provided without resorting to below freezing inlet temperatures.

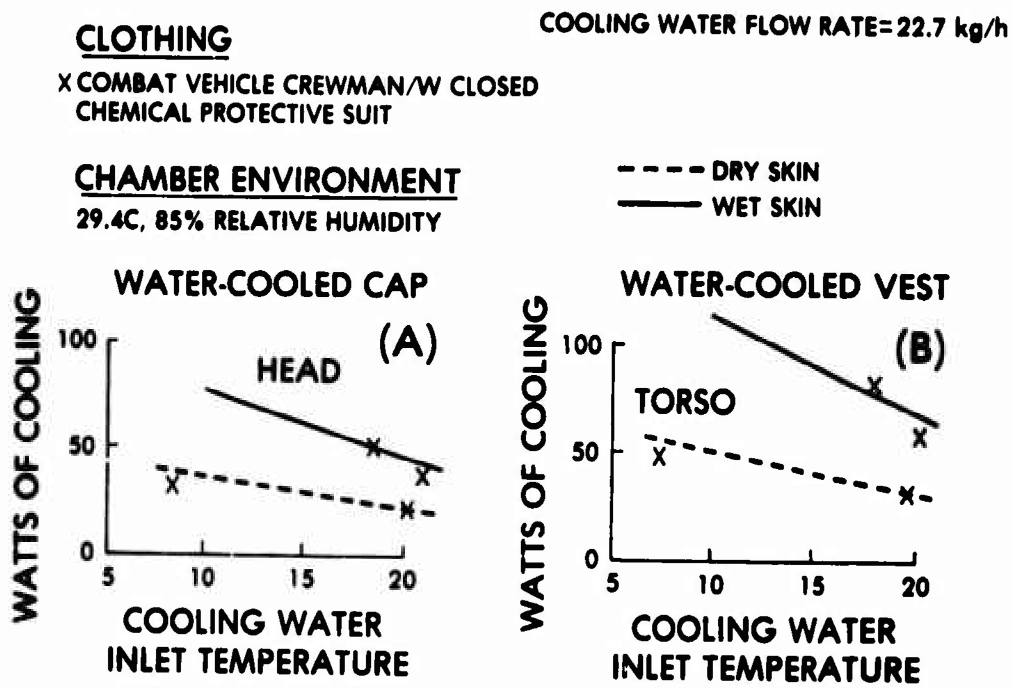

Figure 5 Watts of cooling provided A. to the head by the water-cooled cap and B. to the torso by the water-cooled vest, as a function of the cooling water inlet temperature.

D. TORSO COOLING PROVIDED BY THE WATER-COOLED VEST

Figure 5B, shows the cooling provided to the torso by the water-cooled vest (WCV) as a function of the cooling water inlet temperature. These data were obtained with the manikin dressed in the combat vehicle crewman (CVC) ensemble with the closed chemical protective (CB) suit during exposure to a 29.4°C, 85% relative humidity environment. To provide 100w of cooling over the completely wet skin surface of the torso would require a cooling water inlet temperature of about 12°C. If the skin is dry, the water-cooled vest will not provide 100w of cooling over the torso without having to resort to inlet temperatures below the freezing point of water. Similar to the results for the water-cooled cap, the total cooling measured for a completely wet (maximal sweating) skin surface, minus the expected evaporative heat loss to the environment, is greater than the cooling obtained for the dry (non-sweating) skin condition.

E. HEAD AND TORSO COOLING PROVIDED BY THE WATER-COOLED CAP AND VEST TOGETHER

The distribution of cooling provided over the head and torso by the water-cooled cap with water-cooled vest (WCC/WCV) at a 29.4°C, 85% relative humidity chamber environment is given in Figure 6. About 39% of the cooling provided by this water-cooled ensemble occurs over the head. The remaining 61% is provided over the torso. This translates into cooling 47% of the head area to provide about 39% of the total cooling and cooling 44% of the torso area to provide the remaining 61% of the total cooling (Table V). To provide 100w of cooling over the head and torso areas would require a cooling water inlet temperature of about 21°C for the fully wet skin condition, and of about 5°C for the dry skin condition.

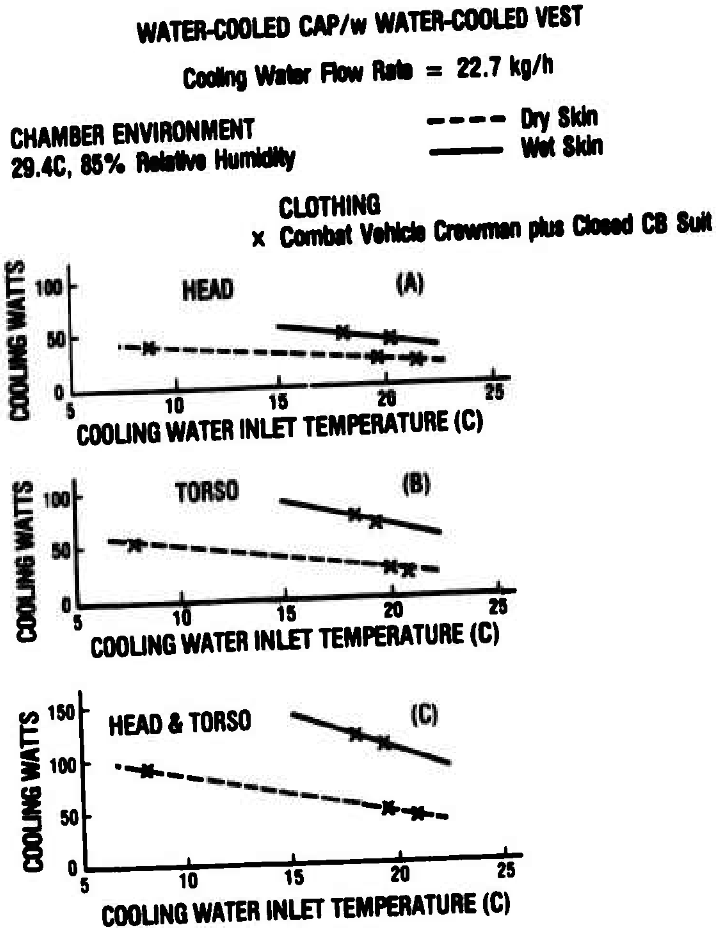

Figure 6 Distribution of the cooling watts provided by the water-cooled cap w/water-cooled vest over: A. the head, B. the torso and C. the resultant cooling over both the head and torso, as a function of cooling water inlet temperature.

F. COOLING PROVIDED OVER THE TORSO, ARMS AND LEGS BY THE WATER-COOLED UNDERGARMENT, SHORT

Figures 7A, B and C give the distribution of the total cooling provided by the water-cooled undergarment, short (WCG_S) over the torso, arms and legs; the proportional cooling is 34% over the torso, 17% over the arms and 49% over the legs (Table VI). These results show that the cooling provided by this water-cooled undergarment is about equally divided between the cooling provided over the legs and that provided over the torso and arms area. The curves plotted in Figure 7D are based on all of the data that were obtained with this water-cooled undergarment. Although the total heat exchange between the manikin surface, the cooling water flowing in the tubing of the water-cooled undergarment and the hot environment is dependent upon the clothing ensemble worn, these curves suggest that the net cooling provided by this water-cooled undergarment is independent of whether the combat vehicle crewman ensemble is worn with or without the closed chemical protective suit. Surprisingly, and importantly, the addition of about 1.4 clo in insulation and the associated reduction of .11 in the evaporative heat transfer properties (i_m/clo) when the closed chemical protective suit is added to the combat vehicle crewman ensemble, has little effect in determining the cooling provided by this water-cooled undergarment over the torso-arms-legs area. Apparently, the differences in the heat transfer properties of these two clothing ensembles are masked by this water-cooled undergarment which must effectively isolate the torso-arms-legs area from the hot environment so that heat exchanges occur primarily between the skin surfaces and the water-cooled undergarment, thus minimizing the effect of adding this (and presumably any other) CB overgarment to the ensemble. A cooling water inlet temperature of about 12°C would provide 200w of cooling over a dry skin; for a completely wet skin inlet temperature could be about 23°C. Extending this curve for a completely wet skin condition shows that a cooling water inlet temperature of about 12°C should provide 400w of cooling which is perhaps enough for even a combat infantryman performing his mission in a hot environment with full CB protection worn.

TABLE VI

DISTRIBUTION OF THE TOTAL COOLING PROVIDED BY EACH OF THE FIVE WATER-COOLED UNDERGARMENTS

WATER-COOLED UNDERGARMENT	PERCENT OF TOTAL WATTS OF COOLING MANIKIN SECTIONS					
	Head	Torso	Arms	Legs	Hands	Feet
Cap	100	---	---	---	---	---
Vest	---	100	---	---	---	---
Cap/Vest	39	61	---	---	---	---
Short	---	34	17	49	---	---
Long	14	22	21	43	---	---
% Manikin Surface Area	8	28	15	34	6	9

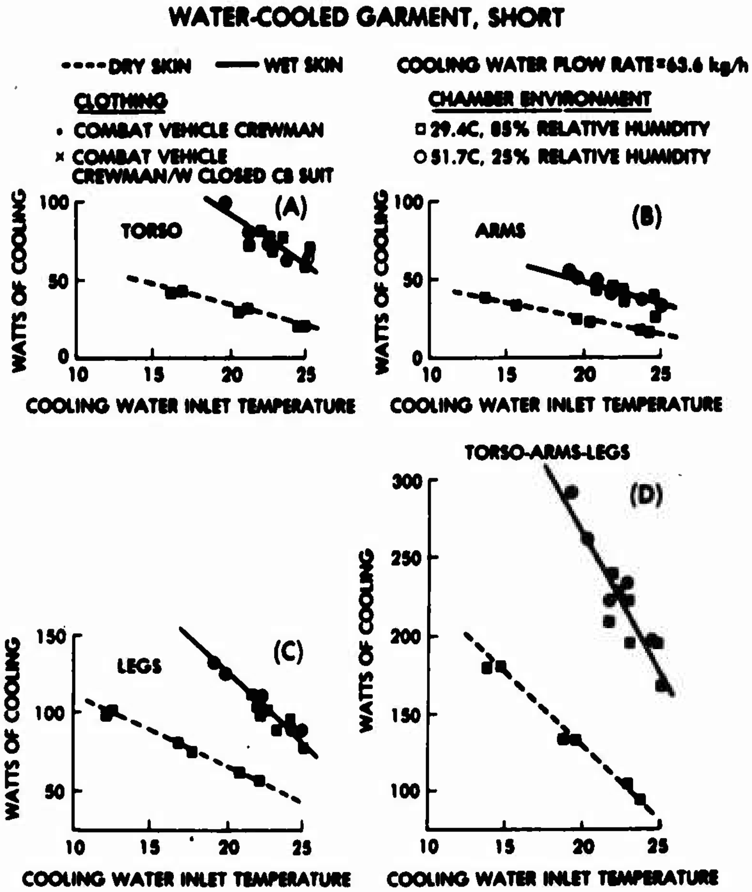

Figure 7. Distribution of the cooling watts provided by the water-cooled undergarment, short, as a function of the cooling water inlet temperature for A. the torso, B. the arms, C. the legs and D. the resultant cooling over the torso-arms-legs.

G. COOLING PROVIDED OVER THE HEAD, TORSO, ARMS AND LEGS BY THE WATER-COOLED UNDERGARMENT, LONG

The distribution of the watts of cooling over the head, torso, arms and legs provided by the water-cooled undergarment, long (WCG_L) is shown in Figure 8. About 14% of this total cooling is provided over the head, 22% over the torso, 21% over the arms and 43% over the legs (Table VI). The cooling provided over the legs is equal to that removed from the arms and torso. To obtain 400w of cooling would require a cooling water inlet temperature of about 19°C for a completely wet skin, while about 7°C would be required for the dry skin condition to obtain the same massive cooling. All of the data obtained for both ensembles and both hot environments are combined in the curves presented in Figure 9; these curves show that the differences in cooling between the two ensembles and between the two hot environments are minimal. As already noted, this experimental result apparently occurs because of the shielding effect of the water-cooled undergarment.

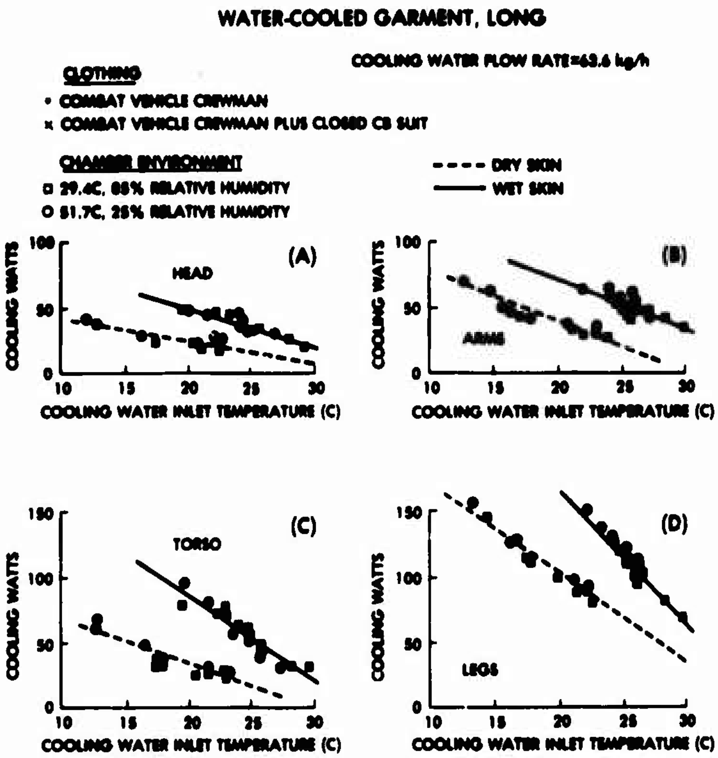

Figure 8. Distribution of the cooling watts provided by the water-cooled undergarment, long, as a function of the cooling water inlet temperature for A. the head, B. the arms, C. the torso and D. the legs.

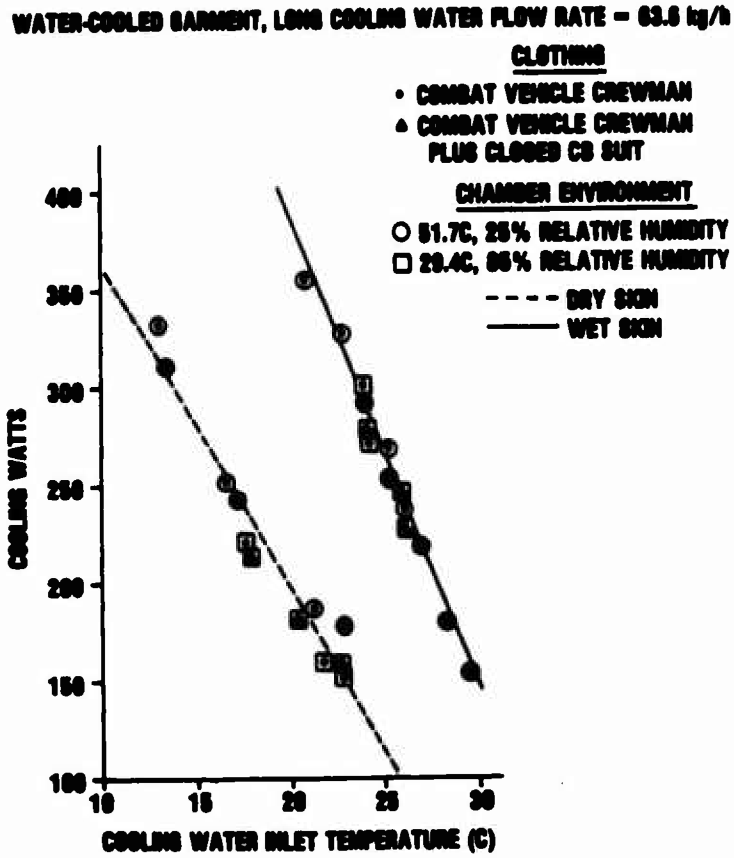

Figure 9. Watts of cooling provided by the water-cooled undergarment, long, over the head-torso-arms-legs as a function of the cooling water inlet temperature.

H. COMPARISON OF THE COOLING PROVIDED BY EACH OF THE WATER-COOLED UNDERGARMENTS

Figure 10 (for the dry skin condition) and Figure 11 (for the completely wet skin condition) give the range of cooling provided by each of the five water-cooled undergarments versus the cooling water inlet temperature. These curves show that at cooling water inlet temperatures above 10°C, the water-cooled cap did not provide 100w of cooling even for a completely wet skin condition; the water-cooled vest would require a completely wet skin condition; and the water-cooled cap with water-cooled vest could provide 100w of cooling for even a dry skin. With the water-cooled undergarment, short, the skin would have to be completely wet if there was a requirement for it to provide 400w of cooling, but the water-cooled undergarment, long, could provide this amount of cooling even if the skin were dry. The rate of increase in cooling, with decrease in cooling water inlet temperature for the completely wet (maximal sweating) skin condition is: 3.1 w/°C for the water-cooled cap; 4.4 w/°C for the water-cooled vest; 7.5 w/°C for the water-cooled cap with water-cooled vest; 17.6 w/°C for the water-cooled undergarment, short; and 25.8 w/°C for the water-cooled undergarment, long. A "comfortable" cooling water inlet temperature of 20°C should provide 46w of cooling using the water-cooled cap; 66w using the water-cooled vest; 112w using the water-cooled cap with water-cooled vest; 264w using the water-cooled undergarment, short; and 387w using the water-cooled undergarment, long. The results demonstrate the obvious conclusion that cooling increases with an increase in body surface area that is covered by a water-cooled undergarment. However, the finding that the greater the skin area covered by a water-cooled undergarment, the less the area exposed to receive heat from a hot environment and the practical elimination of the effects of adding protective clothing was not obvious and, indeed, requires confirmation with human studies.

Expressing these cooling watts as the density of cooling over the body surface covered by the tubing array of a water-cooled undergarment, the water-cooled vest shows the lowest w/m^2 of the five water-cooled undergarments and the water-cooled cap the largest: 657 w/m^2 for the water-cooled cap; 300 w/m^2 for the water-cooled vest; 386 w/m^2 for the water-cooled cap with water-cooled vest; 562 w/m^2 for the water-cooled undergarment, short; and 624 w/m^2 for the water-cooled undergarment, long.

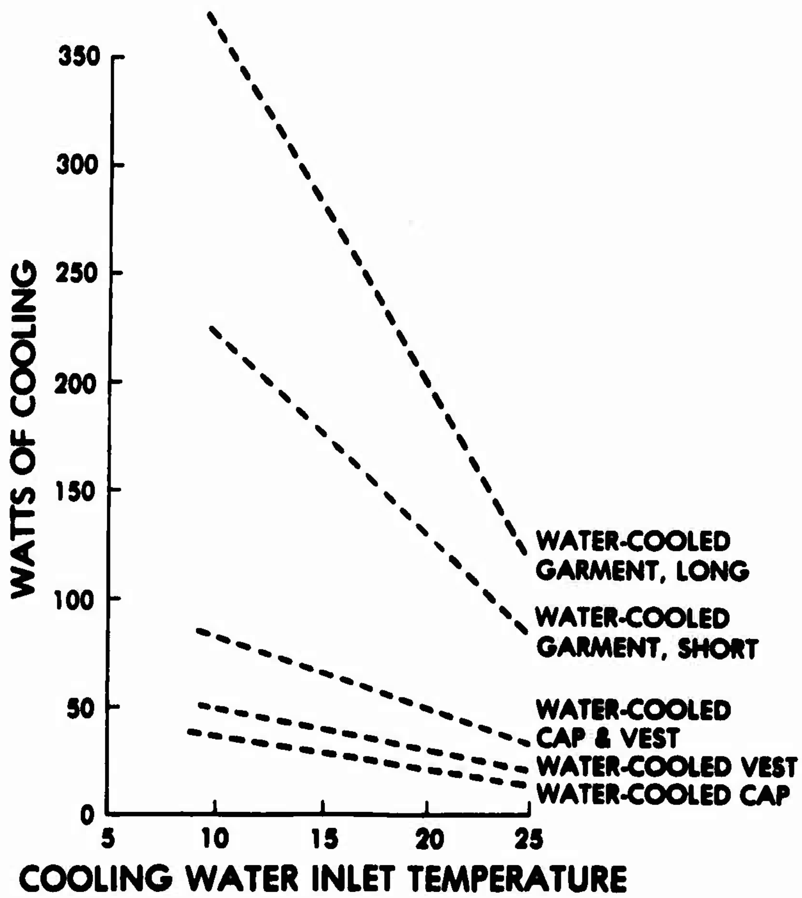

Figure 10. Watts of cooling provided by each of the five water-cooled undergarments as a function of the cooling water inlet temperature for a dry (i.e. non-sweating) skin condition.

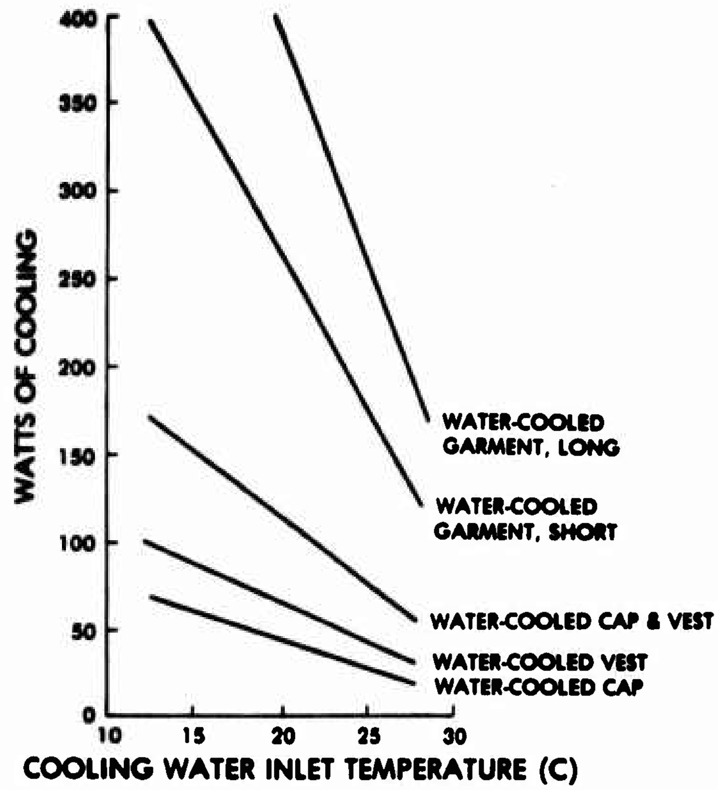

Figure 11. Watts of cooling provided by each of the five water-cooled undergarments plotted against the cooling water inlet temperature for a completely wet (i.e. maximal sweating) skin condition.

I. TOTAL HEAT EXCHANGES FOR EACH OF THE FIVE WATER-COOLED SYSTEMS WHEN DRESSED IN THE COMBAT VEHICLE CREWMAN ENSEMBLE WITH AND WITHOUT THE CLOSED CHEMICAL PROTECTIVE SUIT IN TWO HOT ENVIRONMENTS

The total heat exchanges over the completely wet surface area of the head, torso, arms, hands, legs and feet when water is flowing through the tubing of a water-cooled undergarment are presented in Figures 12 and 13. Figure 12A gives these total heat exchanges (in watts) as a function of the cooling water inlet temperature when each of the water-cooled items is worn with the combat vehicle crewman ensemble in an environment of 29.4°C, 85% relative humidity; Figure 12B gives these totals in an environment of 51.7°C, 25% relative humidity. Figure 13A and B give the totals when the closed chemical protective suit is added to the combat vehicle crewman ensemble. The total heat exchanges for a cooling water inlet temperature of 20°C are presented in Table VII. These curves in Figures 12 and 13 differ from the cooling curves presented in Figures 10 and 11 in that the total heat exchange curves include the cooling provided to the manikin surface by a water-cooled undergarment modified by the heat transfer between the total manikin surface and the hot environment. These total heat exchanges are dependent upon the clothing ensemble worn and the hot environment in which exposure occurs. The difference between the total heat exchanges calculated for the two hot environments decreases with an increase in skin area covered by a given water-cooled undergarment; that is, the contribution to the total heat exchange (sum of the environment heat exchanges and water-cooled undergarment cooling) of a water-cooled undergarment increases with increasing skin surface area covered. Also, whether one or the other clothing ensemble is worn has a major effect on the total heat exchange provided when exposure is in a 29.4°C, 85% relative humidity environment, but less than a 10% difference (except when the water-cooled cap is worn) when the exposure is in a 51.7°C, 25% relative humidity environment.

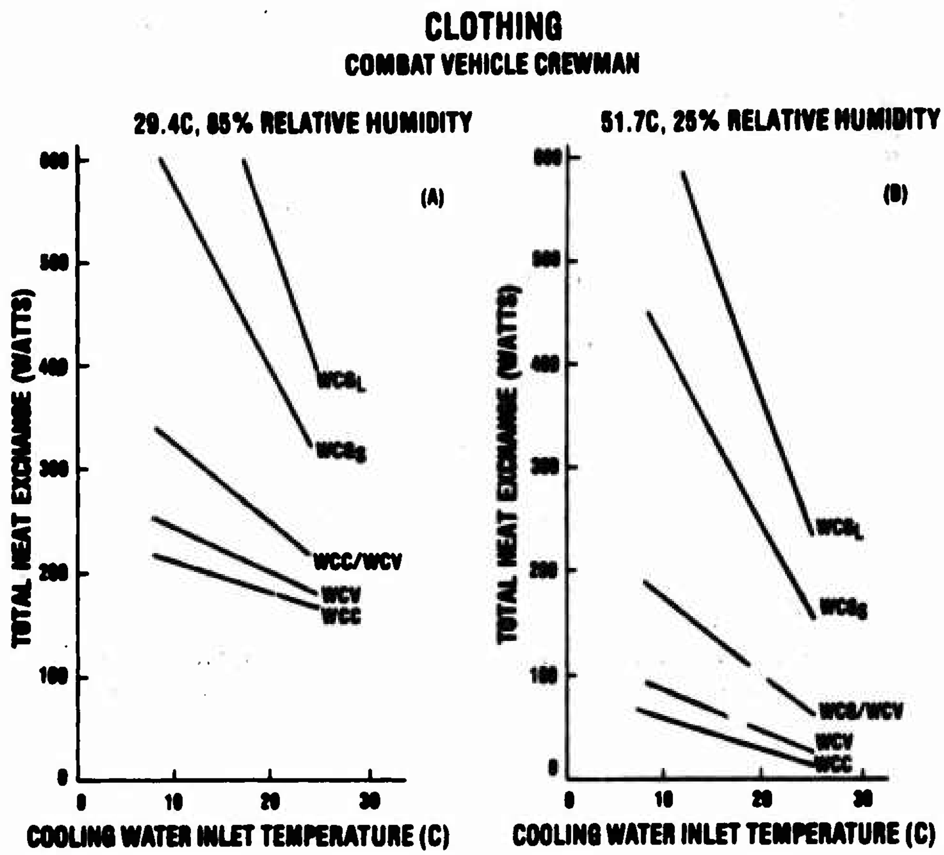

Figure 12. Total heat exchange (watts) over the completely wet (i.e. maximal sweating) skin surface area (1.79 m^2) when each of the five water-cooled undergarments is worn with the combat vehicle crewman (CVC) ensemble in chamber environments of A. 29.4°C, 85% relative humidity and B. 51.7°C, 25% relative humidity.

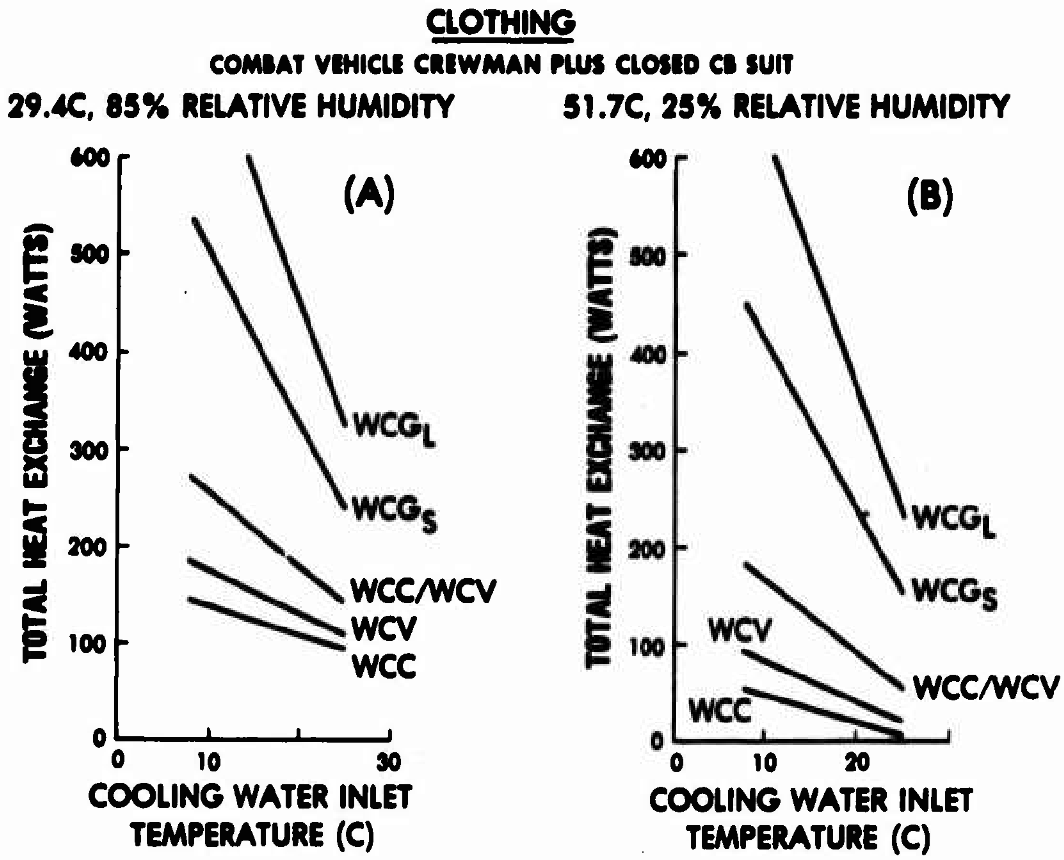

Figure 13. Total heat exchange (watts) over the completely wet (i.e. maximal sweating) skin surface area (1.79 m^2) when each of the five water-cooled undergarments is worn with the combat vehicle crewman (CVC) ensemble w/closed chemical protective (CB) suit in chamber environments of A. 29.4°C, at 85% relative humidity and B. 51.7°C at 25% relative humidity.

TABLE VII

THE TOTAL HEAT EXCHANGE (WATTS) OVER ALL MANIKIN SECTIONS FOR EACH OF THE FIVE WATER-COOLED UNDERGARMENTS WHEN COOLING WATER INLET TEMPERATURE = 20°C (68°F)

WATER-COOLED UNDERGARMENT	COMBAT VEHICLE CREWMAN ENSEMBLE HOT ENVIRONMENTS		COMBAT VEHICLE CREWMAN ENSEMBLE w/CLOSED CHEMICAL PROTECTIVE SUIT HOT ENVIRONMENTS	
	29.4°C,85% RH	51.7°C,25% RH	29.4°C,85% RH	51.7°C,25% RH
water-cooled cap	181	29	110	20
water-cooled vest	200	45	131	41
water-cooled cap w/ water-cooled vest	249	97	180	92
water-cooled undergarment, short	398	245	326	239
water-cooled undergarment, long	522	365	455	365

J. ESTIMATE OF THE REDUCTION IN RATE OF BODY TEMPERATURE RISE BY EACH OF THE FIVE WATER-COOLED UNDERGARMENTS

The additional cooling obtained by using a water-cooled undergarment can reduce the rate of the wearer's body heat storage; i.e. the rate of climb in his mean body temperature can be reduced, eliminated or, if he overcooled, reversed. Body heat storage is related to elevation in mean body temperature by the equation:

$$S = mC_p \Delta T$$

where:

ΔT	=	Elevation in mean body temperature in degrees Celsius
S	=	Body heat storage in watt-hours
C_p	=	Specific heat of body mass in w-hr/kg^{o}C
m	=	weight of man in kg

The rate of storage, in watts, may be related to the rate of rise in mean body temperature by modifying the above equation as follows:

$$S/hr = mC_p (\Delta T/hr)$$

where S/hr is the storage rate in watts and ΔT/hr is the accompanying rate of rise in mean body temperature. By extension, this equation is also applicable for expressing the reduction in rate of rise of mean body temperature corresponding to a reduced rate of heat storage.

Reductions in rate of rise of mean body temperature corresponding to the additional cooling watts of each of the water-cooled undergarments are given in Table VIII for a 70 kg man, using a value of 0.97 w-hr/kg^{o}C for the specific heat of the mass of a body. Konz _et_. _al_. (7) determined a value of 1.2^{o}C/hr by this method for the slowing in rise of mean body temperature based on the amount of cooling provided by an insulated vest containing dry ice. A rough comparison can be made between the calculations for the dry skin condition and those obtained in an earlier water-cooled undergarment study (2). In the earlier study, another type of water-cooled vest showed a decrease of about 2.6°C/hr. In this study the water-cooled vest showed a decrease of 0.4°C/hr for a dry skin condition. Although these calculations are not directly comparable because of different cooling water flow rates, cooling water inlet temperatures, tubing array coverage, clothing, etc., the primary difference between the results for the two water-cooled vests appears to be the greater tubing array coverage over the torso for the water-cooled vest used in the earlier study. The water-cooled vest used in this present study does not have the inherent cooling potential of the earlier water-cooled vest, which covered about 75% of the torso area and utilized uncovered tubing for its cooling surface.

TABLE VIII

ESTIMATE OF THE REDUCTION IN RATE OF RISE OF MEAN BODY TEMPERATURE (°C/hr) PROVIDED BY EACH OF THE FIVE WATER-COOLED UNDERGARMENTS WHEN COOLING WATER INLET TEMPERATURE = 20°C (68°F)

WATER-COOLED UNDERGARMENT	DRY SKIN	FULLY WET SKIN
water-cooled cap	0.3	0.7
water-cooled vest	0.4	1.0
water-cooled cap w/water-cooled vest	0.7	1.7
water-cooled undergarment, short	1.9	3.9
water-cooled undergarment, long	2.8	5.7

4. DISCUSSION

The expectation that providing more and more insulation over a water-cooled undergarment would increase its effectiveness in providing cooling over the skin surface is not supported by these experimental results. The data for the combat vehicle crewman ensemble were essentially equivalent to the data for the combat vehicle crewman ensemble with the closed chemical protective suit. The increase in insulation (1.4 clo) when the chemical protective suit was added over the combat vehicle crewman ensemble did not significantly influence the quantity of cooling provided to the area of the skin covered with a water-cooled undergarment. This finding occurred with either a dry (non-sweating) or completely wet (maximal sweating) skin surface.

These five water-cooled systems, separately or in combination, have the potential to remove the metabolic heat produced in a sedentary (i.e. resting) state (about 80w) or in the highly active state (about 400w) associated with sustained combat infantry operations. The cooling provided by two of these water-cooled undergarments was additive; the water-cooled cap plus the water-cooled vest provided cooling equivalent to that provided by the water-cooled cap with water-cooled vest worn together. However, the watts of cooling per unit surface area covered by a water-cooled undergarment is not constant. For example, the watts of cooling per square meter provided to the head by the water-cooled cap is greater than the watts of cooling per square meter provided to the torso by the water-cooled vest.

The cooling watts obtained using a dry (non-sweating) skin are applicable when the combination of activity and environmental conditions are such that they do not promote sweating or condensation of moisture on the tubing of a water-cooled undergarment. These cooling rates are the minimum watts provided by a particular water-cooled undergarment at a given cooling water inlet temperature. Once sweating is initiated, the process of evaporation of this sweat from the skin surface and transference of the resultant moisture to the environment is modified by the presence of a water-cooled undergarment. Apparently, a water-cooled undergarment not only provides cooling over the skin area covered, but also cools the surrounding air and underlying clothing layers and condenses out much of the water vapor (i.e. sweat) being given off by the skin. In a high temperature and high humidity environment, an evaporation/condensation cycle apparently occurs within the clothing which is similar to the evaporation/condensation cycle occurring within a cold weather impermeable boot worn in arctic environments and reported by Breckenridge (1). This evaporation/condensation cycle within the clothing increases the effectiveness of a water-cooled undergarment. When the skin is wet, this increase in the cooling provided over a completely wet (maximal sweating) skin is considerably greater than that provided over a dry (non-sweating) skin surface; even when the expected evaporative heat loss to the hot environment is subtracted from the total cooling watts for the completely wet skin surface. In this context, such a phenomenon could be considered a synergistic effect. The ultimate source of this "excess" cooling is the cooling water flowing in the tubing of a given water-cooled undergarment. This cool tubing provides a site for the condensation of the water vapor within the clothing.

5. CONCLUSIONS

Wearing the closed chemical protective suit over the combat vehicle crewman ensemble had little effect on the cooling provided by these five water-cooled systems.

This collection of five water-cooled systems separately or in combination have the potential to remove the metabolic heat produced in the sedentary state (about 80w) or in the highly active state (about 400w).

The resultant cooling (sum of the heat exchanges of the skin with the environment and a water-cooled undergarment) when the heat exposure is in a 29.4°C, 85% relative humidity environment is dependent upon which of the two clothing ensembles is worn, but there is less than a 10% difference in the resultant cooling between them (except for the water-cooled cap) when the exposure is in a 51.7°C, 25% relative humidity environment.

In these two hot and humid environments, an evaporation/condensation cycle within the clothing appears to increase the effectiveness of these water-cooled undergarments in providing cooling to a completely wet (maximal sweating) skin surface.

6. FUTURE STUDY PLANS

In the hot and humid environments that can exist within an unventilated, closed combat fighting vehicle, auxiliary cooling is required for the crewmen both when the vehicle is in motion and when it is stationary. The energy requirements for this auxiliary cooling have to come from the vehicle's energy resources. Shapiro (9) has stressed the importance of conserving all vehicle energy resources by operating an auxiliary cooling system only when the vehicle is in motion. Once the vehicle is stationary, the cooling system has to be shut down to conserve the vehicle's energy resources and a passive or minimum energy demand type of individual cooling system has to be used. This need to conserve vehicle energy resources requires a broad-based study of various types of auxiliary cooling systems to provide the technical basis for selecting the most appropriate system. One alternative to using water-cooled undergarments to provide auxiliary cooling to vehicle crewmen is to use individual, air-cooled systems. These air-cooled systems could be employed either separately or as an adjunct to one or more of these water-cooled undergarments studied. Any residual cooling available in the liquid-cooled system, plus the moisture available on the skin and inner clothing layers of the crewmen, could be used to remove excess body heat when both the vehicle and crewmen are inactive. This study will be continued in order to assess the potential of auxiliary cooling systems by examining air-cooled systems, both one that utilizes the hot and humid air of these two environments and one that utilizes conditioned air before it enters the clothing.

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